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PERIOD-LUMINOSITY RELATIONS DERIVED FROM THE OGLE-III FUNDAMENTAL MODE CEPHEIDS

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ABSTRACT

In this Paper, we have derived Cepheid period-luminosity (P-L) relations for the Large Magellanic Cloud (LMC) fundamental mode Cepheids, based on the data released from OGLE-III. We have applied an extinction map to correct for the extinction of these Cepheids. In addition to the VIW band P-L relations, we also include JHK and four *Spitzer IRAC* band P-L relations, derived by matching the OGLE-III Cepheids to the 2MASS and SAGE datasets, respectively. We also test the non-linearity of the Cepheid P-L relations based on extinction-corrected data. Our results (again) show that the LMC P-L relations are non-linear in $VIJH$ bands and linear in KW and the four *IRAC* bands, respectively.

Subject headings: Cepheids — distance scale

1. INTRODUCTION

Recently, the Optical Gravitational Lensing Experiment (OGLE) team released a catalog of the Large Magellanic Cloud (LMC) Cepheids from its third phase of observation (hereafter OGLE-III), as described in Soszyński et al. (2008). In their paper, the Cepheid period-luminosity (P-L) relations in the V and I bands were derived from this OGLE-III catalog without any extinction correction, and it was left for other researchers to correct for the extinction. On the other hand, the current optical band LMC P-L relations available in the literature (see, for example, Udalski et al. 1999a; Sandage et al. 2004; Kanbur et al. 2003; Kanbur & Ngeow 2006; Fouqué et al. 2007) are mostly derived from the OGLE-III predecessor, the OGLE-II catalog (Udalski et al. 1999b). In the JHK band, Persson et al. (2004) derived the P-L relation based on the complete light curves of 92 LMC Cepheids, while Groenewegen (2000) and Fouqué et al. (2007) derived the JHK P-L relations by matching the 2MASS (Two-Micron All Sky Survey) point sources to the OGLE-II Cepheids. At longer wavelengths, the *Spitzer IRAC* band P-L relations were derived by matching the OGLE-II Cepheids and the Cepheids sample from Persson et al. (2004), done in Ngeow & Kanbur (2008) and Freedman et al. (2008) respectively, to the SAGE (Surveying the Agents of a Galaxy's Evolution) archival data.

In this Paper, we attempt to derive the extinction corrected VI band P-L relations by applying an extinction map to the OGLE-III Cepheids (which is not done in Soszyński et al. 2008). We also derive the JHK and the *IRAC* band P-L relations by matching the OGLE-III Cepheids to the 2MASS and SAGE database, respectively. In addition, one unexpected result from the OGLE-II based P-L relation is that the optical LMC P-L relation was found to be non-linear (see, for example, Sandage et al. 2004; Kanbur & Ngeow 2004; Ngeow et al. 2008, and reference therein). We will also test the non-linearity of the extinction corrected OGLE-III P-L relations using rigorous statistical tests.

2. THE DATA

The data for OGLE-III fundamental mode (FU) Cepheids were kindly provided for us by I. Soszyński: this included the celestial coordinates, the mean VI band magnitudes, and the periods for 1848 Cepheids. Further details about this dataset can be found in Soszyński et al. (2008). Throughout this Paper, we have assumed the classification of these FU Cepheids, as given in Soszyński et al. (2008), is robust. Five Cepheids without V and I band mean magnitudes were excluded from the sample. We also excluded the 11 Cepheids with $\log P > 1.5$ (where P is the pulsation period) that only have V band data. The observed magnitudes of these Cepheids are close to the saturation limit of the OGLE-III survey (at $I \sim 13$ mag., Soszyński et al. 2008), hence their photometry may be affected and/or biased.

We also matched the OGLE-III FU Cepheids with

the 2MASS point source catalog (Cutri et al. 2003; Skrutskie et al. 2006), using a search radius of 1”, in order to derive the corresponding P-L relations in the JHK bands. The match did not find the 2MASS counterparts for 71 out of the 1832 Cepheids in our sample within the search radius. The remaining 1761 Cepheids only have one matched 2MASS point source with a mean separation of 0.108” (RMS = 0.110”). We applied the prescription outlined in Soszyński et al. (2005) to convert the single-epoch 2MASS photometry to the mean JHK magnitudes, using the epoch of the 2MASS data, the period and the epoch at maximum light of the Cepheids, and the scaling between the I band and JHK band amplitudes.

Finally, we matched the OGLE-III FU Cepheids with the SAGE data (Meixner et al. 2006) from *Spitzer* observation. The *IRAC* band data was taken from the SAGE Winter ’08 IRAC Archive[1]. In contrast to the SAGE data used in Ngeow & Kanbur (2008), this new SAGE data contains the photometry from both Epoch 1 and 2 observations. Using the same 1” search radius, the query to the SAGE Archive returned 1781 and 1774 unique sources for the Epoch 1 and 2, respectively, and 1759 of them have both the Epoch 1 and 2 photometry. The mean separations for the matched Epoch 1 and 2 sources are 0.222” (RMS = 0.114”) and 0.163” (RMS = 0.147”), respectively. There are a total of 1796 sources after combining the data from the two epochs. We took the averaged values from the two epochs for the matched sources, or kept the single epoch magnitudes if either one of the epochs is available.

3. THE EXTINCTION CORRECTED P-L RELATIONS

There are various ways to estimate the extinction for Cepheids (for example, see the introduction in Kovtyukh et al. 2008). In this Paper, we adopted the extinction map from Zaritsky et al. (2004, hereafter Z04) as a mean to estimate the extinction for individual OGLE-III FU Cepheids, because the Z04 extinction map covers almost the entire LMC. The extinction map from Imara & Blitz (2007) covers a similar region as in Z04 extinction map, but their extinction map is not publicly available. The OGLE team has also published the LMC extinction map based on the OGLE-II red-clump stars (Udalski et al. 1999b), which was later refined by Subramaniam (2005), however the OGLE-II extinction map only covers the central bar region in the LMC. Comparison of the different extinction maps and various methods is beyond the scope of this Paper, and will be presented in future papers. As in Ngeow et al. (2005), we selected the extinction values derived from the cool stars when applying the Z04 extinction map. For a given Cepheid location, the map returns the V band extinction A_V. For the three Cepheids that returned a null value of A_V, we used the mean extinction value of $E(B-V) = 0.10$ appropriate for the LMC. The averaged A_V for the OGLE-III Cepheids is 0.429, which translates to a mean $E(B-V)$ of 0.129. For extinction in other bands, we scaled the A_V values with R_λ/R_V, where R is the total-to-selective extinction coefficient. The adopted values for R are $R_{V,I,J,H,K,3.6,4.5,5.8,8.0} =$ $\{3.24,\ 1.96,\ 0.95,\ 0.59,\ 0.39,\ 0.17,\ 0.12,\ 0.08,\ 0.05\}$. The values in VI band are taken from Udalski et al. (1999b), while for other bands, the values are derived from the Cardelli et al. (1989) extinction law. In addition, we also derived the reddening-free Wesenheit function $W = I - 1.55(V-I)$, with the same expression given in Udalski et al. (1999a), in this Paper.

Outliers of the P-L relations were removed using an iterative 2.5σ clipping algorithm (for example, see Udalski et al. 1999a), where σ is the RMS derived from fitting the P-L relation to the data in a given band. The resulting P-L relations are presented in Figure 1, 2 and 3, respectively. For the 5.8μm and 8.0μm P-L relations,

[1] Using the IRSA’s Gator Catalog Query at `http://irsa.ipac.caltech.edu/applications/Gator/`

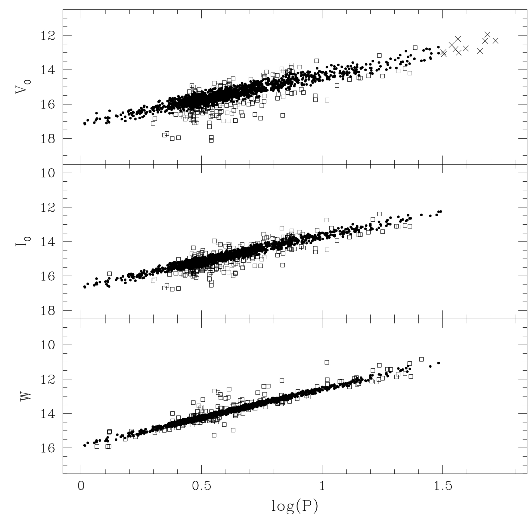

FIG. 1.— The V, I and W band P-L relations derived from the OGLE-III fundamental mode Cepheids. The V and I band mean magnitudes have been corrected for extinction using the extinction map from Z04. The filled circles are the Cepheids used to derive the P-L relations, and the open squares are the rejected outliers. The crosses are the excluded 11 long period Cepheids as described in the text.

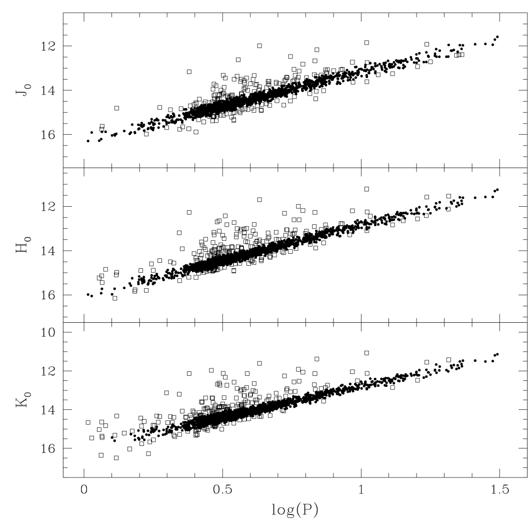

FIG. 2.— The J, H and K band P-L relations derived from matching the OGLE-III fundamental mode Cepheids with 2MASS point source catalog. The JHK band magnitudes have been corrected for random phase and extinction as described in the text. The symbols are same as in Figure 1.

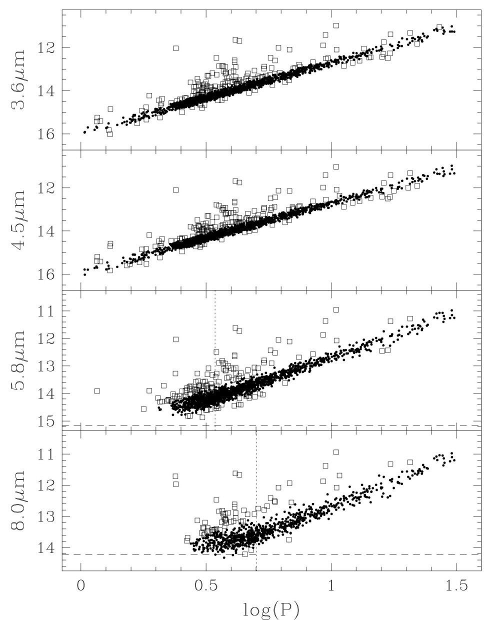

Fig. 3.— The *IRAC* band P-L relations derived from matching the OGLE-III fundamental mode Cepheids with SAGE Archival data. The symbols are same as in Figure 1. The dashed and dotted lines on the lower two panels are the detection limit and the adopted period cut in those bands, respectively.

TABLE 1
The LMC P-L Relation in Various Bands.

Band	Slope	Zero-Point	σ
V	-2.769 ± 0.023	17.115 ± 0.015	0.204
I	-2.961 ± 0.015	16.629 ± 0.010	0.131
J	-3.115 ± 0.014	16.293 ± 0.009	0.121
H	-3.206 ± 0.013	16.063 ± 0.008	0.107
K	-3.194 ± 0.015	15.996 ± 0.010	0.124
3.6μm	-3.253 ± 0.010	15.967 ± 0.006	0.087
4.5μm	-3.214 ± 0.010	15.930 ± 0.006	0.089
5.8μm	-3.182 ± 0.020	15.873 ± 0.015	0.122
8.0μm	-3.197 ± 0.036	15.879 ± 0.034	0.139
W	-3.313 ± 0.008	15.892 ± 0.005	0.069

we an applied additional period cut at the short period end. This is because the magnitudes for the short period Cepheids are approaching the detection limits at ~ 15.2mag. and ~ 14.2mag. in the 5.8μm and 8.0μm band (Meixner et al. 2006), respectively. Further, the 8.0μm P-L relation displays a flattening for Cepheids with $\log P < 0.7$, which is probably due to the larger photometric errors when approaching the limiting magnitudes. A period cut is needed to remove the bias due to this effect. We adopt a period cut at $\log P_{\rm cut} \sim 0.536$ and ~ 0.702 for the 5.8μm and 8.0μm P-L relations, respectively. These period cuts were estimated from a non-linear parametric estimation procedure (same procedure to estimate the break period in the next section). The slopes become shallower without these period cuts. The *linear* version of the P-L relations in all bands is summarized in Table 1. Note that we obtained an (almost) identical W band P-L relation as given in Soszyński et al. (2008).

3.1. *Comparison with the Published Results*

TABLE 2
Comparison of Various P-L Relations.

Ref.	Slope	Zero-Point	N	$\lvert T\rvert$	t
		V Band			
1	-2.769 ± 0.023	17.115 ± 0.015	1675	⋯	⋯
2	-2.760 ± 0.031	17.042 ± 0.021	649	0.208	0.836
3	-2.779 ± 0.031	17.066 ± 0.021	650	0.232	0.817
4	-2.734 ± 0.029	17.052 ± 0.007	716	0.938	0.348
		I Band			
1	-2.961 ± 0.015	16.629 ± 0.010	1640	⋯	⋯
2	-2.962 ± 0.021	16.558 ± 0.014	658	0.036	0.972
3	-2.979 ± 0.021	16.594 ± 0.014	662	0.636	0.525
4	-2.957 ± 0.020	16.589 ± 0.005	692	0.160	0.873
		W Band			
1	-3.313 ± 0.008	15.892 ± 0.005	1501	⋯	⋯
2	-3.277 ± 0.014	15.815 ± 0.010	690	2.321	0.020
3	-3.309 ± 0.011	15.875 ± 0.007	671	0.269	0.788
4	-3.320 ± 0.011	15.880 ± 0.003	686	0.517	0.605
		J Band			
1	-3.115 ± 0.014	16.293 ± 0.009	1586	⋯	⋯
4	-3.139 ± 0.026	16.273 ± 0.006	529	0.836	0.403
		H Band			
1	-3.206 ± 0.013	16.063 ± 0.008	1561	⋯	⋯
4	-3.237 ± 0.024	16.052 ± 0.005	529	1.186	0.236
		K Band			
1	-3.194 ± 0.015	15.996 ± 0.010	1554	⋯	⋯
4	-3.228 ± 0.028	15.989 ± 0.006	529	1.120	0.263
		3.6μm Band			
1	-3.253 ± 0.010	15.967 ± 0.006	1617	⋯	⋯
5	-3.263 ± 0.016	15.945 ± 0.012	628	0.566	0.572
		4.5μm Band			
1	-3.214 ± 0.010	15.930 ± 0.006	1633	⋯	⋯
5	-3.221 ± 0.017	15.927 ± 0.012	635	0.377	0.707
		5.8μm Band			
1	-3.182 ± 0.020	15.873 ± 0.015	931	⋯	⋯
5	-3.173 ± 0.028	15.850 ± 0.022	561	0.272	0.785
		8.0μm Band			
1	-3.197 ± 0.036	15.879 ± 0.034	401	⋯	⋯
5	-3.091 ± 0.039	15.684 ± 0.036	319	1.954	0.051

Note. — Reference: (1) this work; (2) Udalski et al. (1999a); (3) same as (2) but with the updated version given in `ftp://sirius.astrouw.edu.pl/ogle/ogle2/var_stars/lmc/cep/catalog/README.PL`; (4) Fouqué et al. (2007); (5) Ngeow & Kanbur (2008).

In Table 2, we compare our multi-band P-L relations from Table 1 with the published optical VIW band P-L relations derived from the OGLE-II Cepheids (Udalski et al. 1999a; Fouqué et al. 2007), as well as the JHK band P-L relations (Fouqué et al. 2007) and the *IRAC* band P-L relations (Ngeow & Kanbur 2008) that matched the OGLE-II Cepheids to the 2MASS and SAGE (Epoch 1) data, respectively. In this comparison, our philosophy is that it is not sufficient to simply compare whether the P-L slope and/or zero-point obtained by one sample is within one or two standard deviations of the P-L slope and/or zero-point from another sample: this is a necessary but not sufficient condition. What is needed is a simultaneous comparison. An analytical argument showing this has been stated in Ngeow et al. (2008).

We applied the standard t-test (for example, see Bethea et al. 1995) to test the published P-L slopes in Table 2, under the null hypothesis that the slope derived in this Paper, for a given band, is consistent with the published slopes. The T-values calculated from the t-test incorporate the standard deviations of the slopes and the sample variance in the two samples under testing. The corresponding $t_{(\alpha/2,\nu)}$-values were then evaluated from the t distribution with $\nu = N_1 + N_2 - 4$ degree of freedom, where N_1 and N_2 are the number of Cepheids in

the two samples. In our test, we adopted a constant significance level of $\alpha = 0.05$. The values of T and t for each pair of the slopes were given in the last two columns of Table 2. The null hypothesis of equal slopes can be rejected if $|T| > t$.

In general, both agreements and disagreements were found when comparing the slopes to the published results. The disagreements include the $VJHK$ band slopes when compared to those published in Fouqué et al. (2007), the I band slope when compared to the updated version of Udalski et al. (1999a), the W band slope when compared to the slope given in Udalski et al. (1999a), and the 8.0μm band slope when compared it to the slope found in Ngeow & Kanbur (2008). However, agreements were also found for other VIW slopes in the same band. In all cases, the slopes that are in disagreement are either shallower (in VW band) or steeper (in I band) than the rest of the slopes in the same bands. In the JHK band, the slopes from Table 1 were shallower than the counterparts given in Fouqué et al. (2007). Since both sets of P-L relations matched the LMC Cepheids to the 2MASS data and applied the same transformation of the single epoch photometry to the mean magnitudes (as given in Soszyński et al. 2005), the discrepancy of the slopes is due to the different sample size used in both studies (there are about three times more Cepheids in our samples than those in Fouqué et al. 2007)[2]. The slopes in 3.6μm, 4.5μm and 5.8μm P-L relations agree with those given in Ngeow & Kanbur (2008), though the result for 3.6μm band is marginal. The discrepancy for the 8.0μm band P-L relation is mainly due to the additional period cut applied in this Paper.

The difference of the zero-points in the VI band P-L relations between Table 1 and the published results is mainly due to the different extinction maps used in deriving the P-L relations. The P-L relations given in Udalski et al. (1999a) and Fouqué et al. (2007) were derived using the OGLE-II extinction map, with a mean $E(B-V) = 0.147$ (Udalski et al. 1999a). This value is higher than the mean $E(B-V) = 0.129$ found in this paper from the Z04 extinction map (see a similar finding, for example, in Subramaniam 2005; Fingerhut et al. 2007). Hence the derived P-L zero-points will be fainter by ~ 0.06mag. and ~ 0.03mag. in the V and I band, respectively, to those OGLE-II based P-L relations. This difference is indeed seen in Table 2 (except for the I band P-L zero-point from Udalski et al. 1999a). The difference of the P-L zero-points in other bands, that less affected by extinction, may be due to the different sample size used in deriving the P-L relations (see also Soszyński et al. 2008).

4. TESTING FOR NON-LINEAR P-L RELATIONS

As in previous work, the non-linearity of the P-L relation is referred to the two P-L relations separated at 10 days (Sandage et al. 2004; Kanbur & Ngeow 2004; Ngeow et al. 2005, 2008). We have applied a non-linear parametric estimation procedure available in the `SAS` package, which utilizes the Levenberg - Marquardt algorithm, to estimate the break period from the I band data (because the I band light curves are well sampled from large number of observations). The estimated break period is located at $\log P_{\rm break} = 1.006$ (with the 95% confidence limits given by ± 0.170), which is fully consistent to the adopted 10 day period in defining the non-linearity of the P-L relation.

The fitted long ($\log P > 1.0$) and short period P-L relations are summarized in Table 3. At first glance, the difference of the slopes between the long and short period P-L relations in V, K, 3.6μm, 4.5μm, 5.8μm and W band seems to be within $\sim 1.5\sigma$. This may suggest these P-L relations are linear. In contrast, the I, J, H and 8.0μm band P-L relations show a difference of the slopes at $\sim 2.0\sigma$ level or larger. We emphasize again that *testing* for non-linearity by simply seeing if the long and short period slopes are within a certain number of standard deviations of each other is a necessary but not a sufficient condition: a simultaneous comparison using statistical test is needed. Thus a P-L relation can be non-linear even if the short and long period slopes are within 1 to $\sim 2\sigma$ of each other as analytically outlined in Ngeow et al. (2008). Furthermore, Ngeow & Kanbur (2006) also argued that statistical tests are needed to detect the non-linear P-L relation.

In this Paper, we only use the F-test, though several other statistical tests have been applied to the OGLE-II based P-L relations before (Kanbur et al. 2007; Koen et al. 2007; Ngeow et al. 2008). Details for the F-test can be found in Kanbur & Ngeow (2004) and Ngeow et al. (2005), and will not be repeated here. For a large number of data points, $F \sim 3.0$ at 95% confidence level. Hence, the underlying P-L relation is statistically consistent with non-linearity if $F > 3$ (that is, the null hypothesis of linear regression can be rejected). The choice of a 95% confidence level is fairly standard and consistent with our previous work.

The robustness of the F-test has a large literature. Its assumptions are homoskedasticity, normality of errors and independent observations. The last assumption regarding independent observations means that observations of one Cepheid have no bearing on subsequent observations of another Cepheid. Kanbur & Ngeow (2004) checked assumptions of normality and homoskedasticity using OGLE-II Cepheids data and found them to be reasonable assumptions. Homoskedasticity essentially requires there to be not too many outliers in the data, which have been removed in our samples. Ali & Sharma (1996) suggest the F-test is robust to small departures from normality and our large sample size, both with the OGLE-II and OGLE-III Cepheids, further adds to this robustness. For example, Ngeow & Kanbur (2006) appended data from different sources to increase the OGLE-II sample size and found the F-test produced consistent results.

The F-test results were given in the last two columns of Table 3. From this table, The F-test results clearly suggest that the IJH band P-L relations are non-linear, in contrast the K band P-L relation and the 3.6μm to 5.8μm P-L relations are linear. These results support the previous finding of the non-linear/linear LMC P-L relations from the OGLE-II and MACHO Cepheids (Ngeow et al. 2005; Kanbur & Ngeow 2006; Ngeow et al.

[2] If restricted to $\sim$ 610 OGLE-III Cepheids that are common to OGLE-II, the P-L slopes we obtained in JHK band are -3.135 ± 0.022, -3.228 ± 0.020 and -3.213 ± 0.024, respectively. When compared to the P-L relations from Fouqué et al. (2007), the corresponding T- and t-values are $|T_{J,H,K}| = \{0.118, 0.290, 0.409\}$ and $t_{J,H,K} = \{0.906, 0.772, 0.683\}$.

TABLE 3
F-Test Results of the P-L Relations.

Band	Slope$_S$	Zero-Point$_S$	σ_S	N_S	Slope$_L$	Zero-Point$_L$	σ_L	N_L	F	$p(F)$
V	-2.823 ± 0.031	17.143 ± 0.018	0.202	1566	-2.746 ± 0.165	17.122 ± 0.195	0.230	109	3.18	0.042
I	-3.004 ± 0.020	16.651 ± 0.012	0.130	1553	-2.775 ± 0.111	16.440 ± 0.129	0.132	96	5.77	0.003
J	-3.150 ± 0.019	16.312 ± 0.011	0.119	1486	-2.909 ± 0.120	16.075 ± 0.139	0.142	100	5.24	0.005
H	-3.246 ± 0.017	16.085 ± 0.010	0.106	1461	-2.989 ± 0.096	15.832 ± 0.113	0.117	100	7.90	0.000
K	-3.212 ± 0.021	16.006 ± 0.013	0.124	1449	-3.057 ± 0.101	15.845 ± 0.117	0.125	105	1.57	0.209
3.6μm	-3.254 ± 0.013	15.967 ± 0.008	0.086	1509	-3.233 ± 0.068	15.944 ± 0.082	0.100	108	0.06	0.946
4.5μm	-3.228 ± 0.014	15.938 ± 0.008	0.088	1524	-3.185 ± 0.071	15.903 ± 0.085	0.104	109	1.05	0.352
5.8μm	-3.164 ± 0.035	15.861 ± 0.025	0.122	813	-3.275 ± 0.083	15.984 ± 0.099	0.125	118	0.78	0.460
8.0μm	-3.036 ± 0.100	15.746 ± 0.083	0.142	286	-3.348 ± 0.086	16.058 ± 0.102	0.127	115	2.70	0.069
W	-3.329 ± 0.010	15.900 ± 0.006	0.068	1585	-3.338 ± 0.084	15.934 ± 0.096	0.084	84	2.90	0.055

Note. — σ is the dispersion of the P-L relation. Subscripts $_S$ and $_L$ refer to the short ($\log P < 1.0$) and long period Cepheids, respectively. The $p(F)$ is the probability under the null hypothesis of single line regression, for the given F value and the degree of freedom.

2008; Ngeow & Kanbur 2008), and extend the non-linear/linear results further to the Cepheids from the OGLE-III sample. The F-test results on the V, W and 8.0μm P-L relations are worth a further discussion.

In our previous work, the LMC V band P-L relation shows a highly significant F-test result for non-linearity (Ngeow et al. 2005; Kanbur & Ngeow 2006; Ngeow et al. 2008), with a large F-value and a p-value that is significantly smaller than 0.05. The F-value listed in Table 3 is 3.18, which appears to be close to the $F = 3.0$ threshold at 95% confidence level[3] However, hypothesis testing works with p-values for the chosen statistics under the null hypothesis. Hence, the probability of having an F-value as large as 3.18 is smaller than 0.05. Therefore, the V band P-L relation *does* show evidence of non-linearity from the F-test.

For the Wesenheit function, Ngeow & Kanbur (2005) and Ngeow et al. (2008) found that the LMC Wesenheit function, using the OGLE-II data, derived from the optical band is linear. The $F = 2.90$ (with $p = 0.055$) from Table 3 suggests the W band P-L relation found in this paper is also linear. However, if the $p = 0.042$ for the computed V band F statistics in Table 3 is considered to be non-linear, then the same attention must be given to the fact that the $p = 0.055$ for W band P-L relation which is close to being considered linear. Our explanation for this has been that the non-linearities in the P-L and period-color (P-C) relations cancel out in producing a linear Wesenheit function (Ngeow & Kanbur 2005; Koen et al. 2007). Koen et al. (2007) also suggested that with a larger sample and more accurate data, the "cancellation" of non-linearities in the PL/PC relation will not necessarily be exact leading to a non-linear Wesenheit function.

Ngeow & Kanbur (2008) found the 8.0μm P-L relation is non-linear, in contrast to the linear F-test result given in Table 3. This discrepancy is due to the period cut applied at a rather large period (note that no period cut was applied in Ngeow & Kanbur 2008). In fact, the 8.0μm P-L relation becomes non-linear if $\log P_{\rm cut} < 0.69$ is adopted. The non-linear 8.0μm P-L relation found in Ngeow & Kanbur (2008) could be caused by the incompleteness of the data at the faint end when approaching the detection limit. Another possibility is that mass-loss may plays some role in longer wavelength P-L relations to make the P-L relations non-linear (Neilson et al. 2008). Detailed study of the effect of mass-loss on the *IRAC* band P-L relations, based on the OGLE-III Cepheids, is currently underway, and will be presented in a future paper.

[3] If the confidence level is lowered, say to 90%, then the corresponding F-value will be decreased to ~ 2.3. In this case the F-test result for the V band P-L relation clearly shows that it is non-linear.

5. INCLUDING THE LONGER PERIOD CEPHEIDS

In previous sections, we excluded the Cepheids with $\log P > 1.5$ from the OGLE-III sample, which only have the V band data. Including these Cepheids the linear version of the V band P-L relation is almost identical to the relation given in Table 1. However, the slope of the long period P-L relation becomes steeper (-2.823) as compared to the slope given in Table 3 (-2.746) if these Cepheids were included. Previous studies (see, for example, Sandage et al. 2004; Kanbur & Ngeow 2006; Ngeow et al. 2008) found that the long period V band P-L relation is shallower than the short period counterpart. Hence the steeper slope may suggest these longer period V band Cepheid data should not be included in the sample.

It is possible to increase the number of long period Cepheids and extend the period coverage beyond $\log P = 1.5$, by including the additional Cepheids from the literature. This has been done, for example, in Sandage et al. (2004). However, one criticism has been that the published long period Cepheid data may not be in the same photometric system as in the OGLE survey (Fouqué et al. 2007). The on-going "OGLE Shallow Survey of the LMC Cepheids" is aimed to observe the longer period LMC Cepheids in the same photometry system as in OGLE-III. Hence, it is better to wait for the data released from this survey before appending additional longer period Cepheids to our sample.

6. CONCLUSION

In this Paper we derive the $VIJHKW$ and the four *IRAC* band LMC P-L relations based on the OGLE-III Cepheids. The Cepheid data were corrected for extinction by applying the Z04 extinction map. We matched the OGLE-III Cepheids to the 2MASS point sources, and the single-epoch 2MASS photometry was transformed to the mean magnitudes. For the *IRAC* band data, a straight average from the SAGE Epoch 1 and 2 archival data were adopted, which should closer to the mean magnitudes than those used in Ngeow & Kanbur (2008).

We compare our P-L relations to the published results using the t-test. For the published optical P-L relations

that used in the comparison, 2/3 of them show a good agreement on the P-L slopes to our results. For the JHK and *IRAC* band, the t-test results show that our P-L slopes disagree and agree (except for the 8.0μm band P-L slope) to the published results, respectively.

We further test the non-linearity of the P-L relations using the F-test to the OGLE-III Cepheids, and found that the LMC $VIJH$ band P-L relations are non-linear but linear in KW and the four *IRAC* bands, respectively. It has to be cautious that the 5.8μm and 8.0μm P-L relations may be affected by incomplete bias at the faint end and/or mass-loss. It is worth pointing out that both MACHO and OGLE-III samples show the same non-linear/linear results in $VJHK$ bands, where both samples have relatively large number of Cepheids and cover the similar region in the LMC.

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